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Monitoring Sources of Nuclear Radiation in Space
Part I — Early 1984 Observations

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Nuclear radiation from the reactor-powered satellite COSMOS 1579 has been monitored by the gamma-ray spectrometer (GRS) on NASA's Solar Maximum Mission satellite (SMM). Gamma rays from the RORSAT were detected about every 4 days as it passed within ~ 500 km of SMM. In addition events attributed to positrons emitted from the outer shell of COSMOS 1579 were detected on the average of once every ~ 1.5 days. These positrons were detected at large distances ($\lesssim$ 5000 km) from COSMOS after being stored in the earth's magnetic field for seconds or minutes. The rate of the positron detections is about a factor of two higher than observed for most of the earlier RORSAT's detected by SMM.

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19. ABSTRACTS (Continued)

At present this increase is unexplained. The qualitative features of the measured gamma-ray spectrum from COSMOS 1579 are similar to those of preceding satellites; however, the spectral features are clearer. We present a model for the origin of these features which suggests the presence of significant amounts of beryllium, sodium, potassium, molybdenum and lithium and/or hydrogen lying with tens of gm/cm^2 of material. There is also spectral evidence for the presence of either iron or aluminum. Based on this model we obtain a conservative lower limit to the thermal power of the reactor on COSMOS 1579. This lower limit is 30 kW.

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MONITORING SOURCES OF NUCLEAR RADIATION IN SPACE
PART I — EARLY 1984 OBSERVATIONS

I. INTRODUCTION

The Soviet Union launched COSMOS 1579, a nuclear-powered ocean surveillance satellite on June 29, 1984. This was the first such system to be put in orbit following the well publicized reentry of COSMOS 1402 in February 1983. Nuclear radiation emitted by the satellite was detected within four days following its launch by the gamma-ray spectrometer (GRS) on board NASA's Solar Maximum Mission satellite (SMM). Direct observations of gamma-radiation were made within about 500 km when COSMOS 1579 was not occulted by a significant amount of material in SMM. Positrons and electrons produced in the outer layers of COSMOS 1579 were detected at distances up to ~5000 km. These particles reached SMM after being stored along the magnetic field lines connecting positions of the two satellites. The positrons are unambiguously identified by the 0.511 MeV gamma-ray line produced when they annihilate in local material near the SMM detector.

The SMM gamma-ray spectrometer first detected radiation from a nuclear reactor in space in 1980, following the launch of COSMOS 1176. Details of the history of these measurements can be found in an earlier report (Share et al. 1989). Spectral measurements during four close encounters with COSMOS were detailed. The spectrum of radiation was hard and extended up to about 7 MeV, above which the intensity fell off quickly. This fall-off was attributed to neutron capture gamma rays from either beryllium or molybdenum in the reactor or to neutrons from the reactor captured in SMM's NaI detector. We were not able to unambiguously identify the source of the radiation. A feature near 0.5 MeV was also apparent in the spectra which was broader than the instrument's response to a narrow line. We attributed this feature to a blend of lines including the positron-electron annihilation line at 0.511 MeV.

Twenty-six positron annihilation events were detected by SMM that were attributable to positrons emitted by COSMOS 1176. Some of these observations were made when SMM and COSMOS were separated by more than 5000 km. By using the locations of the spacecraft and an algorithm for tracing particles in the earth's magnetic field, we showed that most of the events could be explained by positrons emitted by COSMOS 1176 which temporarily filled a magnetic flux tube traversed by SMM. In most cases there was clear evidence for the expected westward drift of the positrons prior to detection by the gamma-ray spectrometer. Several charged particle events were also detected by plastic scintillation detectors in both the GRS and the Hard X-Ray Burst Spectrometer experiment on SMM. For these events there was clear evidence for an eastward drift of the electrons in the earth's magnetic field. Hones and Higbie (1989) have performed detailed calculations which confirmed this magnetic storage origin for the annihilation and charged particle events observed by SMM.

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The gamma-ray spectrometer has been in almost continuous operation since its launch in 1980; there has been no degradation in its performance. With the exception of a six month period from October 1983 to April 1984, when the tape recorders on SMM were turned off, SMM has provided a monitor of Soviet reactors in space. In April 1984 the attitude control system of SMM was repaired by the Shuttle astronauts and most of the experiments returned to full operation. Although SMM was not boosted up to 550 km as planned, calculations indicated that it will remain in a stable operating mode until about 1990.

Following its observation of COSMOS 1176, the SMM gamma-ray spectrometer detected nuclear radiation from each of the subsequently launched RORSAT's: COSMOS 1249, 1365, 1372, 1402, and 1579. In this report we provide details of measurements made of nuclear radiation from COSMOS 1579 and compare its characteristics with the emissions from earlier RORSAT's.

II. OBSERVATIONS OF COSMOS 1579

A. EVIDENCE FOR INCREASED PARTICLE RATE

The first detection of nuclear radiation from COSMOS 1579 was made only 4 days following its launch on June 29, 1984. A charged particle event, attributable to electrons emitted from the satellite and temporarily stored in the earth's magnetic field, was detected by the plastic scintillation counters in the spectrometer. During its 90 days in operation, SMM detected about 29 additional electron events from COSMOS 1579. During that same time period, an automated search of the SMM data revealed 57 annihilation radiation events attributable to positrons from COSMOS. This corresponds to an average of one detection every 1.5 days. This rate of detections appears to be about a factor of two higher than the average rate for COSMOS 1176, 1365, and 1372. Part of the increase could be accounted for by a decrease in the background radiation in the SMM detectors or by a coincidental arrangement of the orbits of the satellites so that SMM had a higher probability of crossing field lines filled by positrons from COSMOS 1579.

B. GAMMA-RAY SPECTRUM OF COSMOS 1579

We have summed the measurements from the five most significant observations of COSMOS 1579 to produce a spectrum of the detected radiation. The integration time for each of these observations was about 49 sec and was centered about the time of closest approach of the satellites. Background has been subtracted from the spectrum, but no correction has been made for instrument response (see below discussion for an explanation). We therefore plot the count-rate spectrum of detected events and not the flux of incident radiation as a function of energy. This spectrum is shown in Figure 1 and exhibits significant emission extending up to at least 7 MeV. Several features marked by the arrows are evident.

Before we can address the interpretation of the features of the spectrum, we must first resolve a fundamental question concerning its origin. In our earlier report (Share et al. 1989), we concluded that the spectrum could have either been produced by gamma rays or neutrons emitted from the COSMOS satellites. We list below the arguments that lead us to conclude that the dominant source of the spectrum is gamma radiation from COSMOS:

1. Thermal neutrons from the reactor are ruled out because they would take a few minutes to reach SMM; this conflicts with observed time histories.

2. The off-axis response of SMM is consistent with a gamma-ray origin; fast neutrons would have shown significantly less attenuation.

3. The observed spectrum is too hard to be consistent with what is expected from fission neutrons inelastic scattering in the NaI detector (Bendt and Jurney, 1978). Furthermore there is not enough material around the detector to thermalize a large fraction of the neutrons and thereby produce a harder neutron capture spectrum.

4. The flux of MeV gamma-radiation from nuclear reactors is several times the neutron flux.

The overall shape of the count-rate spectrum shown in Figure 1 is consistent with that observed from COSMOS 1176 (Share et al. 1989). Preliminary analysis also indicates that the gross features of the spectra of the other detected COSMOS satellites are also similar. In order to display the data shown in Figure 1 as a photon spectrum, we need to start with an approximate representation of the input spectrum. This is true because the technique used to unfold the instrument response is not unique. This technique works well when the spectrum can be defined as a relatively simple continuum, with superimposed lines whose energies and widths can be estimated. Such is the case in our analysis of gamma rays emitted during solar flares. However, the spectrum displayed in Figure 1 exhibits evidence for a more complicated situation. Either there are several lines that are blending together to form broad features which cannot be resolved, or there are individual gamma-ray lines which have undergone considerable scattering before reaching SMM. The latter should have the effect of producing an edge in the spectrum where the line would have normally appeared and a continuum of scattered photons extending to lower energies. As we would expect many gamma-ray lines produced in COSMOS 1579 to originate near its reactor, it is realistic to assume that there is a considerable amount of overlying material (eg. tens of gm/cm^2) which can severely attenuate and degrade the emission. For purposes of our ensuing discussion we shall therefore assume that the spectrum shown in Figure 2 originates in large part from embedded sources. This premise is supported by a trial fit to the data which we describe later in this section. We believe that a detailed modelling of the reactor and its support structure will be required to confirm our model.

Under the assumption that the spectrum in Figure 1 is due primarily to embedded sources of line emission, we shall attempt to infer some of the materials irradiated by neutrons from the reactor. It is best to start our analysis at the high-energy end of the spectrum. An expanded view of the region near 7 MeV and designated by "g" in Figure 1 is shown in Figure 2. The sharp fall-off denoted by "gl" occurs near ~6.9 MeV. Also of interest is a relatively weak line feature (~2.5 σ) near about 7.7 MeV designated by "g2". Likely sources for this feature are the 7.724 MeV neutron capture line from aluminum, and 7.631 and 7.645 MeV lines from iron.

It is possible to explain the spectral features designated by "a" through "g" in Figure 1 by energy-degraded gamma-ray lines produced by neutron capture in five or six materials, plus the 0.511 MeV positron annihilation line. The materials are beryllium, molybdenum, sodium, potassium, and lithium or hydrogen (possibly LiH). Other materials alsc contribute, but this relatively simple explanation has a basic appeal. Table 1 lists the different degraded lines which may contribute to the labeled features. The relative strength of the line for a given material are listed by percent. We find evidence in the spectrum for all of the intense lines expected from the materials listed. The positron annihilation line is basically a secondary line produced by the higher energy gamma rays as they interact in the reactor housing and structure of the satellite. All of the other lines listed are produced by neutron capture and are emitted promptly, with the exception of the 1.368 and 2.750 MeV lines from sodium. These are radioactive decay lines from ^{24}Na, which has a half-life of ~15 hr. Another possible contributer to the 6.9 MeV feature is boron, but there is no evidence for strong line features expected at 4.4 and 4.7 MeV. For this reason we do not believe that boron plays a significant role in the spectrum at high energies.

In order to illustrate our premise that the observed spectrum is a composite of degraded neutron capture lines from COSMOS 1579, we have formed a model gamma-ray spectrum consisting of a power-law continuum with 12 lines superimposed. These 12 lines were derived from Table 1. This model for the incident gamma-ray spectrum was modified by the instrument response and fit to the observed data summed differently than those plotted in Figure 1. This summation improved the energy resolution of the display at the expense of the statistical significance of the points. The fit to this spectrum is shown by the histogram in Figure 3. It is clear from this fit that the broad features are not due to the energy resolution of the spectrometer. Excess emission appears at energies below most of the lines. This excess low-energy emission is what we have attributed to degradation in the material of COSMOS 1579. Although we do not believe that it is likely, we cannot rule out the possibility that some the the broad features are due to a multiplicity of lines unresolved by the NaI detector.

C. ESTIMATE OF THE POWER OF THE REACTOR

We describe a method for obtaining a lower-limit estimate of the power of the reactor on COSMOS 1579. This follows as a consequence of our assumption that the observed spectrum is due to degraded gamma-ray lines from neutron capture. If we assume that the degraded photons from a specific line form a flat spectrum (i.e. a shelf) up to the line's energy, then we can estimate the intensity of the unscattered line. For example the 6.9 MeV feature, which we primarily attribute to beryllium, is assumed to form a shelf of about 1 count/s-MeV from the 0 to 6.9 MeV. This yields an estimated rate of about 7 counts/s. Dividing this by an effective area for an interaction in the NaI of $100 cm^2$, we obtain a total flux at SMM of about 0.07 gamma/cm^2-s for the degraded 6.9 MeV feature. Our goal in doing this is to estimate the flux of neutrons captured in the material of COSMOS 1579. Therefore we sum up the intensities from other apparently degraded line features, under the restriction that only one line is used for each material. The intensities from no other line features attributable to Be are added, but we do take into account that only 64% of the neutron capture gamma rays appear in the 6.9 MeV feature. Conservatively then we only add the inferred 2.75 MeV feature from ^{24}Na and the inferred 2.0 MeV feature from lithium or hydrogen.

We estimate that the total gamma-ray flux from these three materials as viewed by the SMM spectrometer is about 0.3 gamma/cm^2-s. In this way we are obtaining a lower limit on the gamma-ray flux from COSMOS 1579. For an average separation of about 300 km, this implies that the rate of gamma-ray emission at COSMOS is about 3×10^{15} gamma/s.

Again to obtain a lower limit on the power, we shall assume that one of these neutron capture gamma-rays is produced for each fission. This requires that about 40% of the fission neutrons are captured by the surrounding material and do not result in a further fission or escape from the satellite. On this assumption, the fission rate in the reactor is about 3×10^{15}/s. For 200 MeV released in each fission, this implies a minimum total power of about 90 kW or about 30 kW thermal (for an assumed thermal efficiency of 30%).

III. ACKNOWLEDGMENTS

We wish to especially acknowledge our colleagues Prof. E.L. Chupp and Dr. D.J. Forrest of the University of New Hampshire. It was under their direction that this successful experiment was built. Their assistance in the understanding of the instrument's performance has been essential. Detailed ephemeris information has been provided by R. Cote and R. Berry of NAVSPASUR. Support for the scientific analysis of the SMM data at NRL is provided by NASA contract S14513D.

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Hones, E.W. and Higbie, P.R. 1989, Science 244, 448-451.

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TABLE 1

Contributions to the Gamma-Ray Spectrum of COSMOS 1579

Feature	Origin	(%)	Energy (MeV)
"a"	sodium	(60)	0.472
	positron annihilation		0.511
"b"	molybdenum	(07)	0.720
	potassium	(51)	0.770
	molybdenum	(37)	0.778
	molybdenum	(15)	0.848
	beryllium	(26)	0.853
	sodium	(22)	0.870
"c"	sodium	(100)	1.368
"d"	sodium	(17)	2.027
	lithium	(89)	2.032
	potassium	(10)	2.074
	hydrogen	(100)	2.223
"e"	sodium	(15)	2.517
	sodium	(100)	2.750
	sodium	(10)	2.862
"f"	beryllium	(34)	3.367
	beryllium	(12)	3.443
	sodium	(15)	3.558
	sodium	(19)	3.982
"g"	beryllium	(64)	6.809
	molybdenum	(03)	6.919

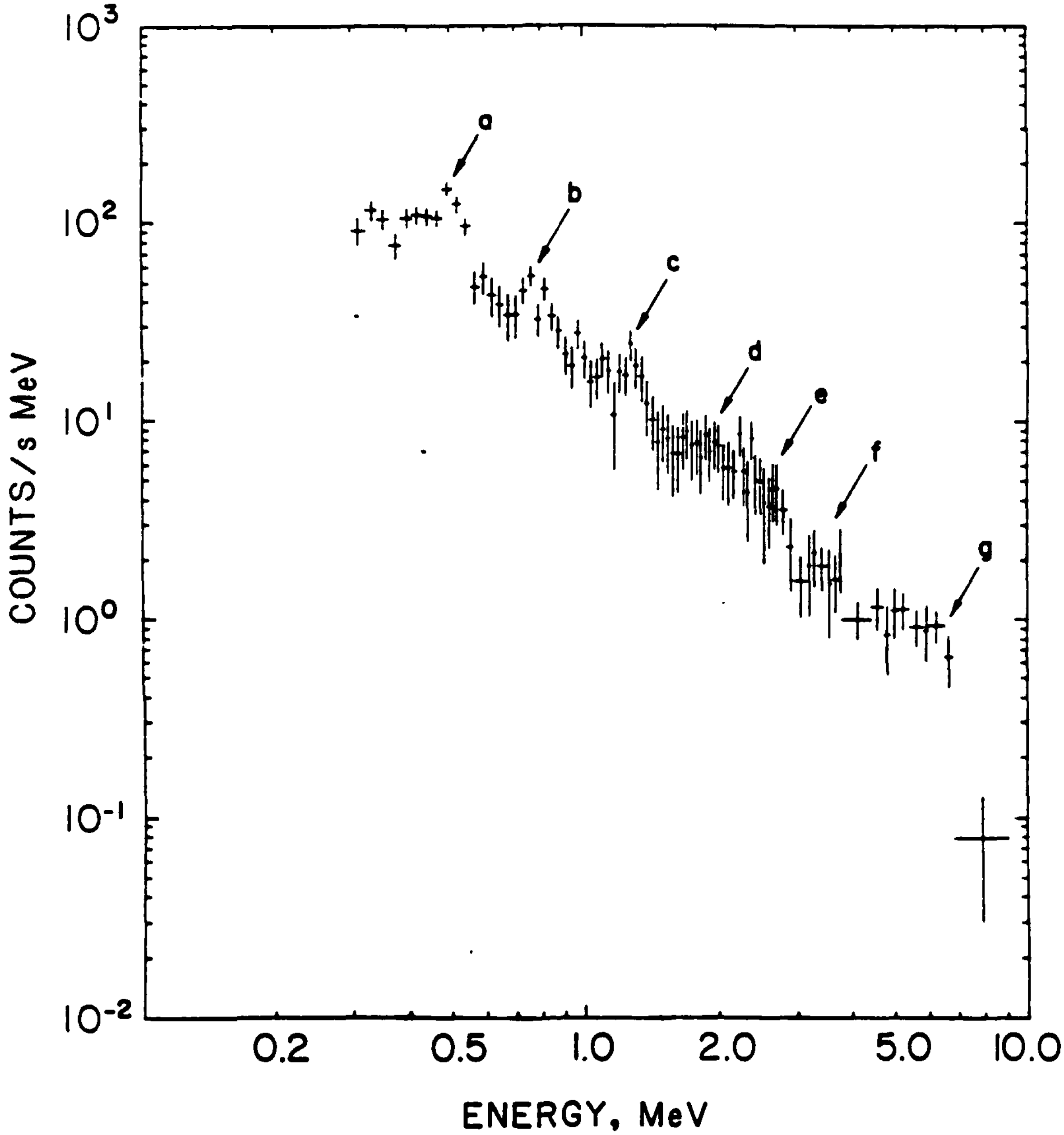

Fig. 1 Summed count-rate spectrum of gamma-radiation detected by the SMM spectrometer in five close encounters with COSMOS 1579. The labeled features are discussed in the text and in Table 1.

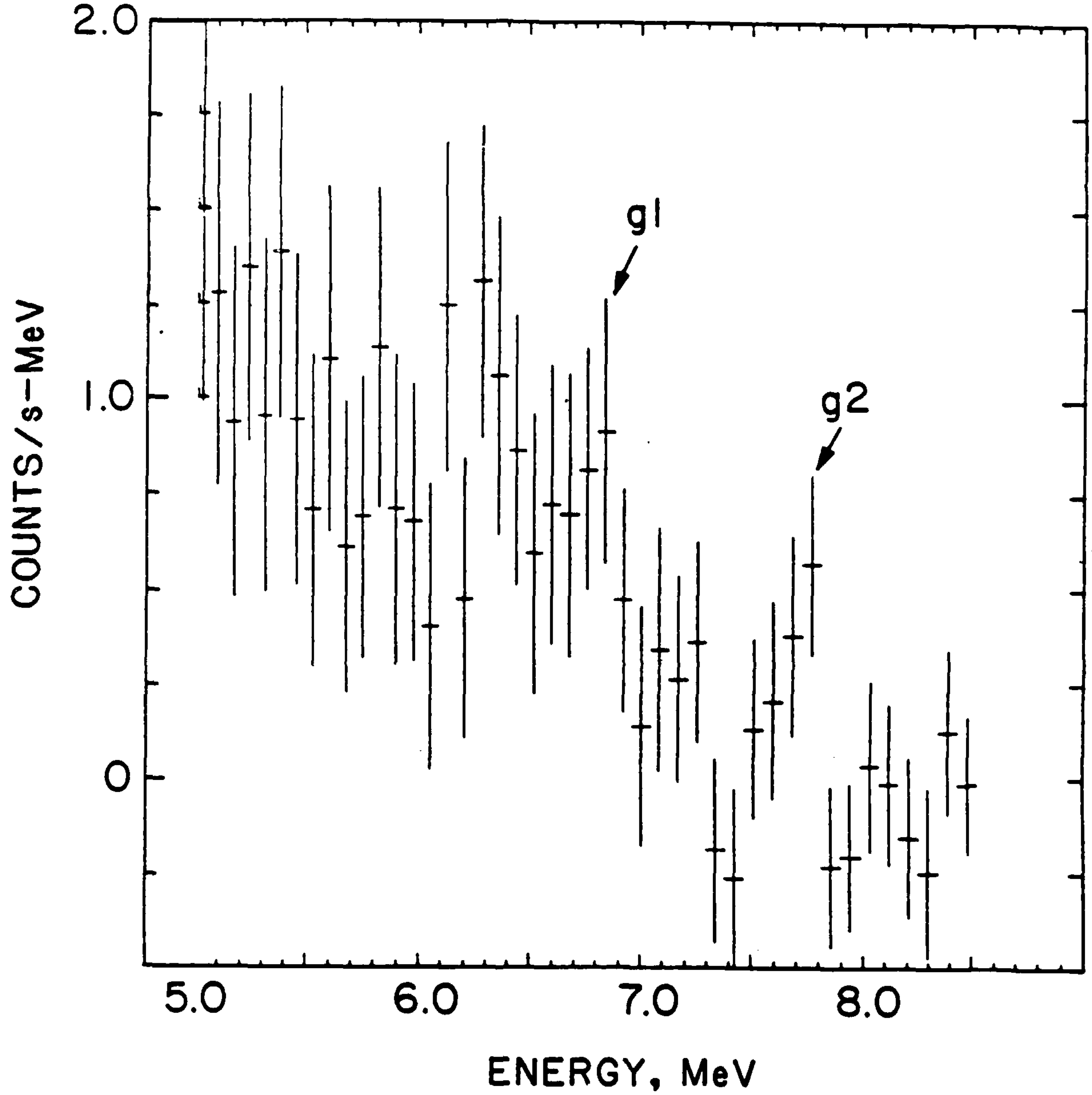

Fig. 2 A blow-up of the count-rate spectrum of gamma-radiation from COSMOS 1579 shown iu Fig. 3 near 7 MeV.

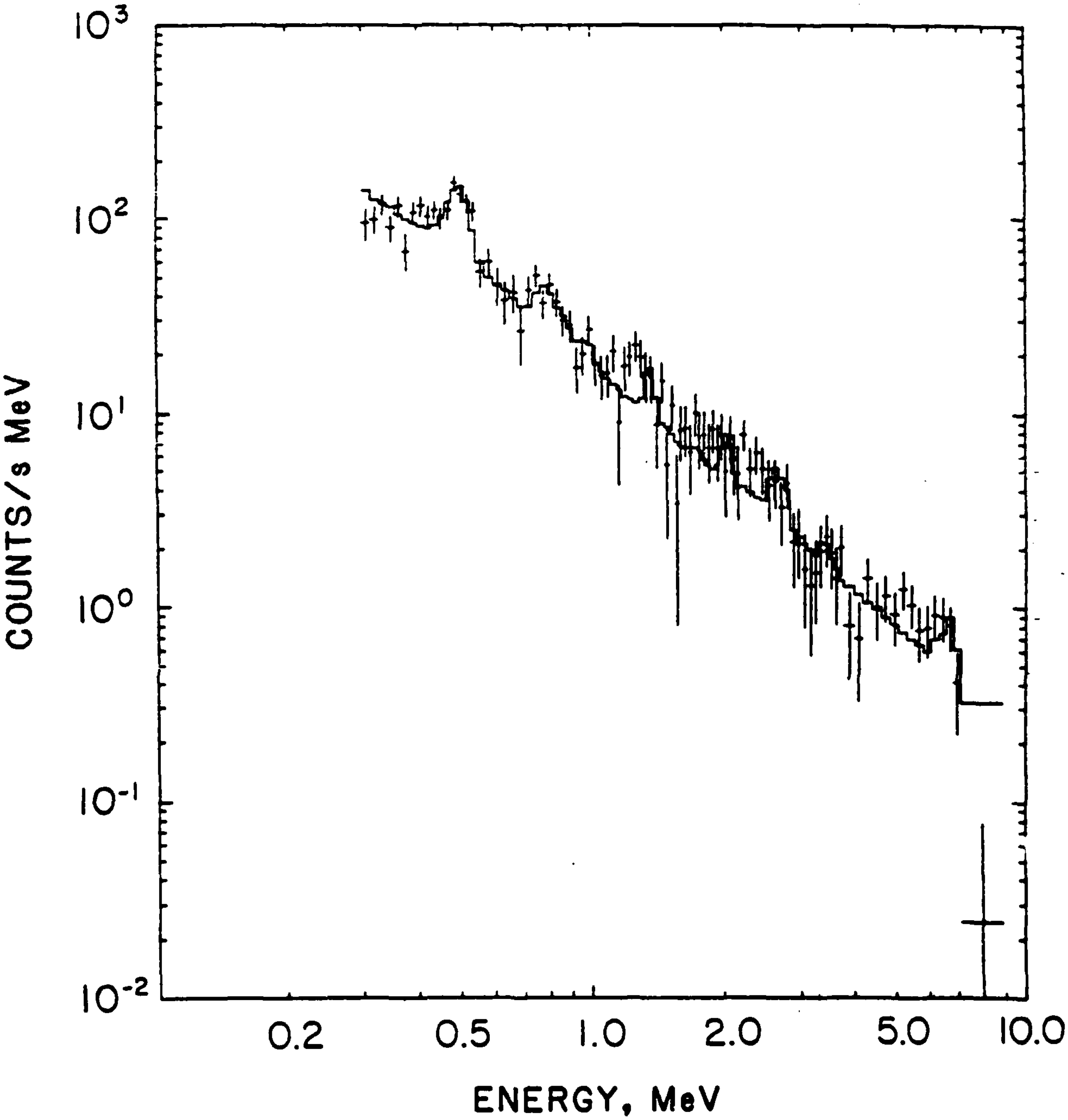

Fig. 3 Summed count-rate spectrum of gamma-radiation from COSMOS 1579 fit by a model with 12 gaussian lines superimposed on a power-law continuum. The histogram shows the best fit of this model to the data after passing through the instrument's response function.